CALIBRATED ORBITING OBJECT PROJECT, (COOP) CONE TIP HEATER INSTALLATION AND CHARACTERIZATION

Ben Brown

07 August 2009

Technical Note

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14. ABSTRACT
In this experiment, heaters were installed inside the Calibrated Orbiting Object Project (COOP) cone tip for the purpose of controlling the temperature of the cone tip on orbit. Heater performance characterization was accomplished for two different heater configurations and the differences in performance are discussed. Heater performance was characterized by measuring the temperature of the tip at various current set points and comparing these to those predicted by a one-dimensional conductive heat transfer model.

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1.0 SUMMARY

In this experiment, we installed heaters on the inside of the Calibrated Orbiting Object Project (COOP) cone tip for the purpose of radiating heat from the outside of the tip. Once the heaters were installed, a characterization test was performed using thermocouples on both sides of the tip to determine the amount of heat being conducted through the tip from the heaters. The characterization test involved measuring temperatures of the tip at various current values. The average outer temperature on the tip came out to be 47.68°C at 1.34A while the temperature on the inner heater read 79°C. Although this data provided a good model for the heat transfer, it was not as good as we had hoped. Theoretical models were produced to show the heat transfer with the heaters bonded directly to the aluminum instead of the inside paint. This showed considerable gains in heat transfer through the tip, so we decided to reapply the heaters based on that model. We peeled off the heaters, removed the inside paint where the heaters were placed with abrasives, and reinstalled the heaters directly on the aluminum with a higher temperature range epoxy. By removing a layer of paint, a new characterization test granted us better heat transfer results. The new average outer temperature on the tip was 54.22°C and the temperature of the heater was 59.24. These reading were taken also at 1.34A.

2.0 INTRODUCTION

This experiment was designed to measure the heat transfer through the COOP cone tip from the inside to the outside surfaces. The heat will be generated by the 10 heaters glued to the inside of the tip. The temperature characterization is being done to predict the outside temperature of the tip on orbit for calibration purposes. 1-D conduction heat transfer will be the method of calculating the predicted temperatures of the outside of the tip. The temperatures will be measured at six current settings with the last setting being the highest current that the heaters are rated for. The purpose of these calculations is to determine if the heaters can reach max power without the paint and epoxy exceeding their operational temperatures. It is also important to record the inside and outside temperatures at the various current levels so proper heat transfer modeling for the whole spacecraft can be carried out. The difference between the temperatures on the outside of the tip and the heaters is an indication of the amount of heat that is being conducted through the tip. These experiments were performed at Kirtland AFB. The heat transfer was calculated by using the following two equations.

$$q'' = \frac{T_{in} - T_{out}}{\sum R_{t,cond}}$$

Equation 1

where q'' is heat transfer rate per unit area in W/m^2,
 T_{in} is the temperature of the inside of the tip in °C,
 T_{out} is the temperature of the outside of the tip in °C, and
 $R_{t,cond}$ is the total thermal resistance for conduction per unit area in m^2K/W.

The thermal resistance for conduction per unit area is defined as

$$R_{t,cond} = \frac{L}{k}$$

Equation 2

where L is the thickness of the resistance boundary in m and
 k is the thermal conductivity in W/mK.

3.0 METHODS, ASSUMPTIONS AND PROCEDURES

The resistance of each heater was initially verified to be ~157Ω using a Fluke model 179 multimeter. The dial on the meter was set to Ohms and the display was automatically adjusted to the easiest form of the number (mΩ, Ω, MΩ, etc.). Then four of the heaters were installed on the inside of the tip using Eccobond 285 with catalyst 24. The heaters were taped to the cone and the wires tack-glued down so they would stay in place during the curing process (see Figure 1 (a) below). The inner four heaters were installed first because the tape used to hold the heaters in place got in the way of where the other six heaters would be placed. After a 24-hour ambient cure, the tape was removed from the first four heaters. Then the other six heaters were installed on the inside of the tip slightly higher than the previous four heaters. The epoxy for the other six heaters underwent a 23-hour ambient cure. Figure 1 (b) shows all the heaters installed.
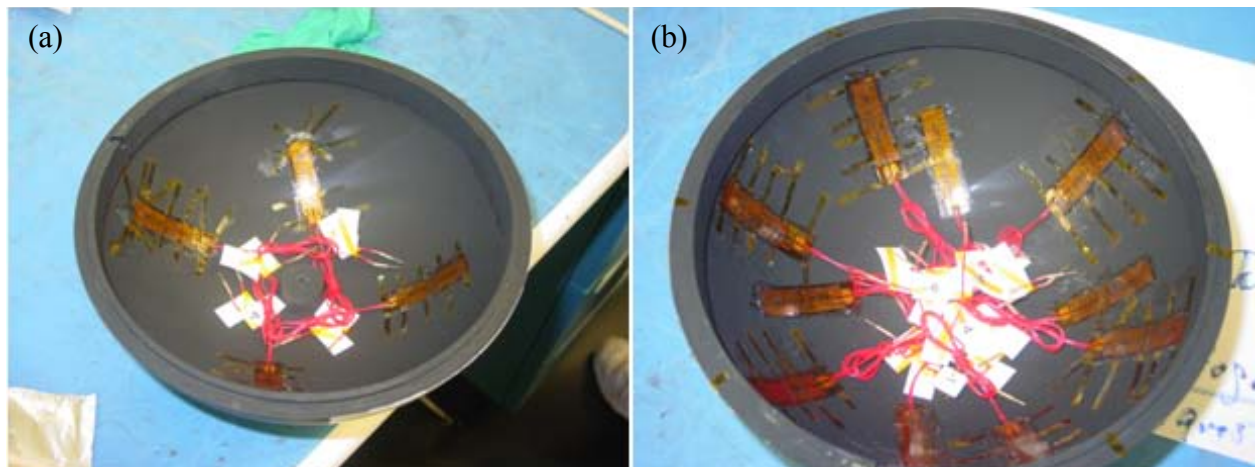
Figure 1: (a) Heaters 1-4 installed. (b) All 10 heaters installed.

After all the heaters had cured, the resistance of each heater was checked against its previous resistance value to be sure it didn't change significantly. The most variance of resistance was +/- 4Ω. Also the isolation resistance to the chassis was tested using the Fluke 179 to be sure there was no current going from the heaters through the chassis. 0 Amps was the value shown on the meter for each heater. The next step was to connect six thermocouples to the outside of the tip. Two of the thermocouples were attached to the black area and four were attached to the white area. Placement of the thermocouples is shown in Figure 2.

Figure 2: Thermocouple Placement Diagram (top view).

Another thermocouple (TC7) was installed directly on a heater as a reference to show the actual temperature of the heaters during the characterization test. All of the heater wires were connected to a single node on a breadboard which was supplied with 28 volts via a power supply. See Figure 3 for a photo of the final installation.
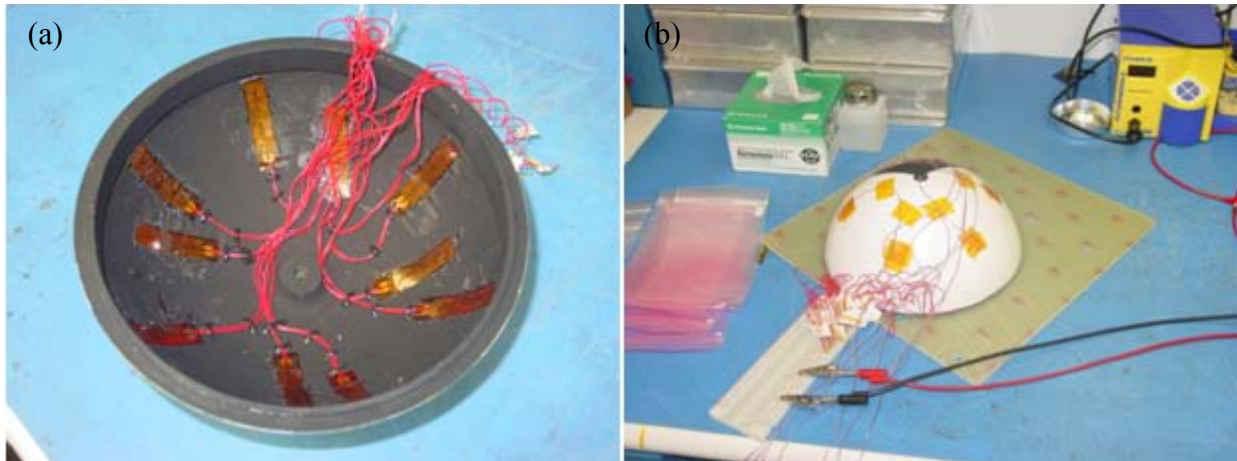
Figure 3: (a) All 10 heaters installed and leads secured. (b) Six thermocouples installed.

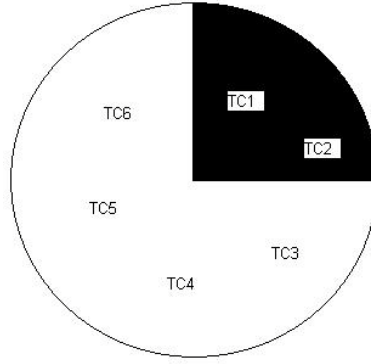Characterization of the tip involved applying current to the heaters and monitoring the temperature inside and outside the tip via the thermocouples which are connected to a data acquisition card. LabView was used to monitor the thermocouples. The temperature measurements were recorded at 0, 0.45, 0.89, 1.34, 1.55, and 1.74 Amps once all the thermocouples reached steady state ($\Delta Temperature/\Delta Time = 0.1°C/s$). Once the temperature stabilized at 1.34A, we projected that the temperature of the heaters would rise above 100°C at 1.74A based on the rate of temperature increase for previous current intervals. This was a concern because the upper temperature for the epoxy to operate correctly was 105°C. Therefore, the power supply was turned up to 1.74A and the temperatures were monitored until the heater temperature reached 98°C. At this point, the power was turned off and the tip cooled down. After

the tip had significantly cooled, the power was turned back on and different levels of current were tested to determine what amount would induce a heater temperature of ~100°C. We determined that the inner temperature stabilizes to 99.3°C at 1.55A. Therefore, temperature measurements were recorded at 1.55A.

The team decided that the difference in temperature between the inside and outside was too large and that removing the inside paint where the heaters are placed would allow better heat transfer. Therefore, a theoretical model was created for the heat transfer of the tip of this prediction. It showed that the outer temperature would decrease by 11.57°C. Therefore the team opted to reinstall the heaters to fit the theoretical model. For the reinstallation procedure, the heaters were peeled off of the tip while a heat gun was used to weaken the chemical bond of the epoxy. Two of the heaters were damaged beyond use – one can be seen in Figure 4 below. The non-salvageable heaters were replaced with new ones.
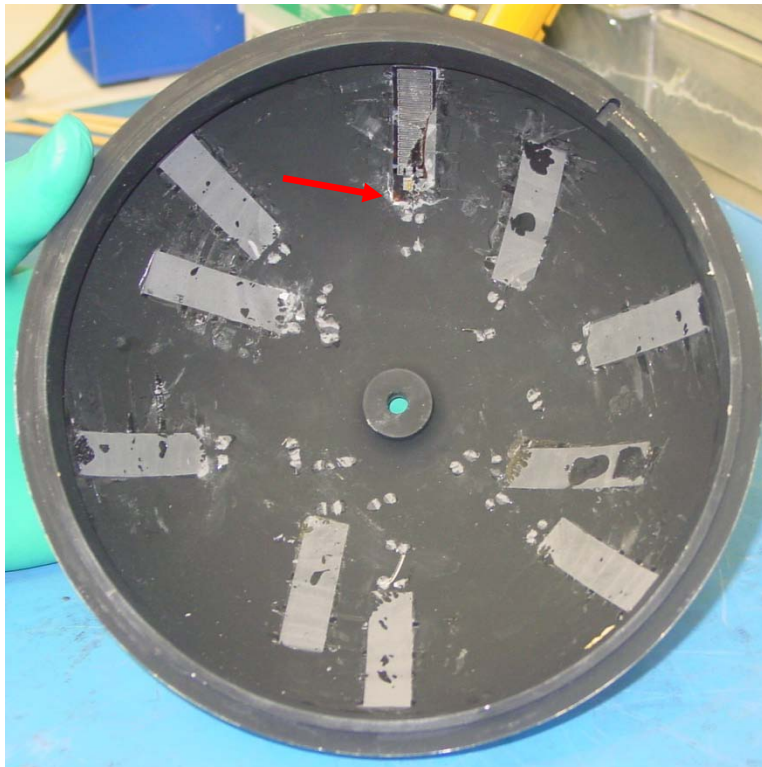
Figure 4: Post heater removal with remnant of one heater highlighted with red arrow.

Copper tape was used to mask the entire inside surface of the tip except where the heaters were placed to protect it from the abrasive used to remove the paint. The paint (along with the glue) where the heaters were placed was removed using a die-grinder. The copper tape then was removed and the tip cleaned with isopropyl alcohol. See Figure 5 below.
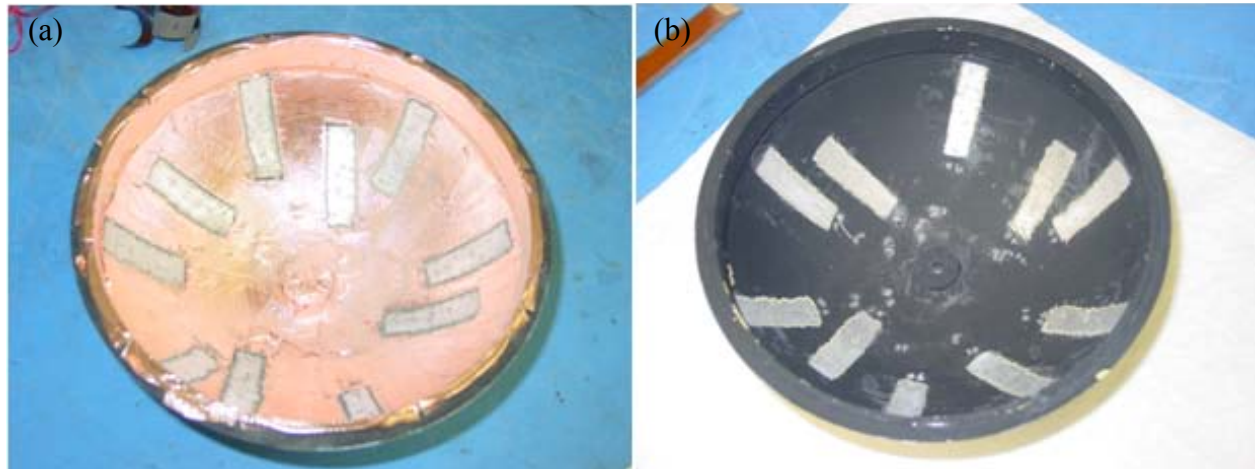
Figure 5: (a) Copper tape installed and the heater areas ground to the aluminum. (b) Copper tape removed and cleaned with IPA.

Similar to the previous heater installation, the heaters were installed in two sets. The first set was the inner four heaters and the last set was the outer six heaters. The curing process was different than before because of the use of a different catalyst; catalyst 11. These heaters were placed in an 80°C oven to cure (see Eccobond 285 data sheet) for 16 hours for each set.

The resistances of the heaters were tested before and after the heaters were replaced as well as after the epoxy cured to make sure that there were not any significant changes. The heaters were also isolation tested after the cure to ensure there was not any current traveling from the heaters through the aluminum tip.

Eight thermocouples were installed on the tip; six on the outside and two on the inside. One thermocouple was also placed on top of a heater. This was the same configuration as last time except for the eighth thermocouple which was placed on the inside surface of the paint for additional information about where the heat is transferring. The heaters were connected to a power supply via a breadboard and the thermocouples were connected to a data acquisition card. Figure 6 below shows this configuration. As the current was increased at intervals of ~0.45A starting from 0A to 1.74A, the measurements were recorded from the thermocouples.

Figure 6: Thermocouples installed and power supply connected to heaters.

4.0 RESULTS AND DISCUSSION

The individual resistance measurements of the heaters right out of the box are shown below in Table 1. All the heaters were within +/- 4Ω of the specified 157 Ω.
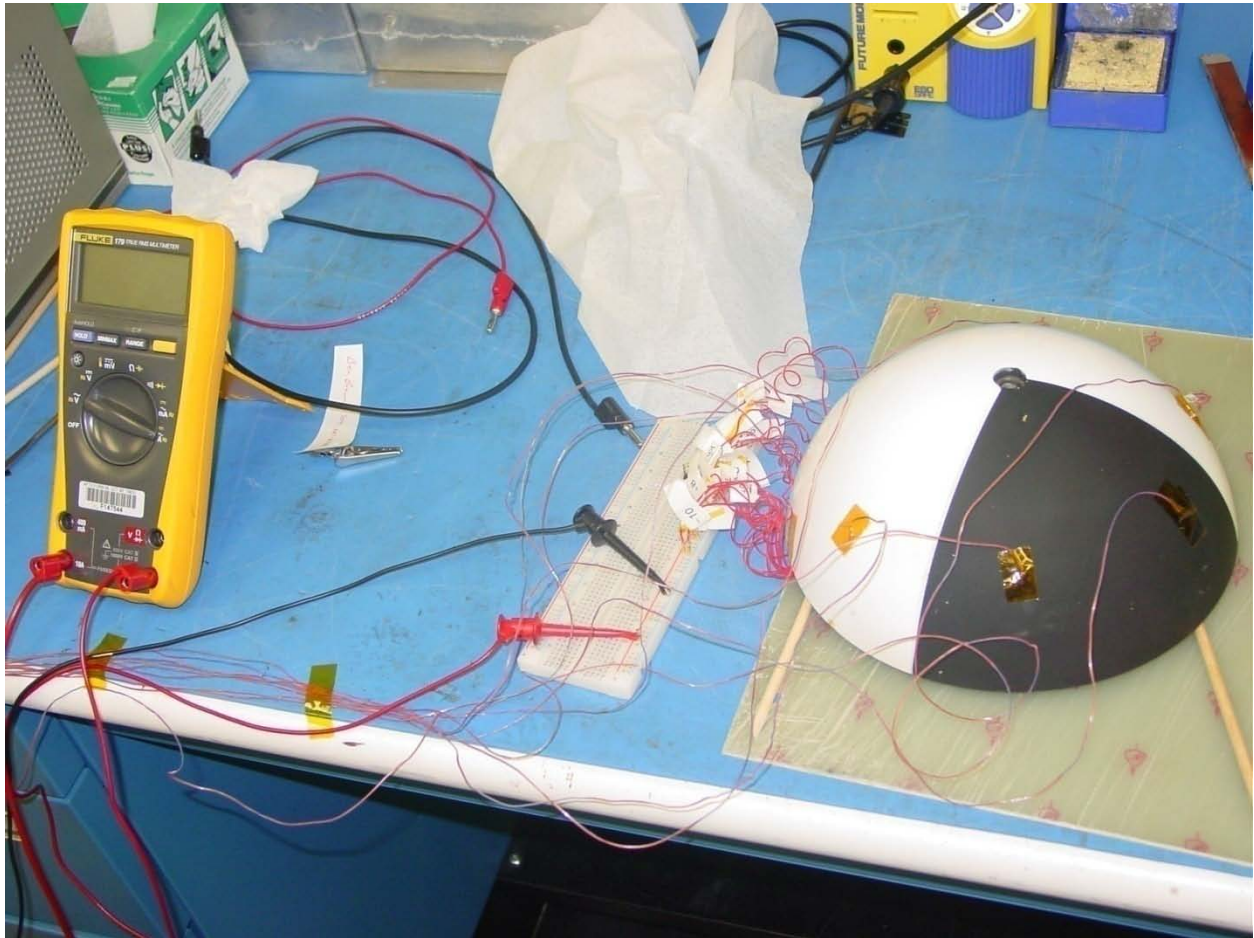
Table 1: Initial resistance values of heaters.

Heater #:	1	2	3	4	5	6	7	8	9	10
Resistance (Ω)	157.7	160.3	157.6	154.7	157.5	160.9	158.8	158.4	154.2	157.5

The second resistance measurements and isolation measurements are recorded in Table 2 below. These were taken after the heaters were installed. Variations in resistance are within 0.4 Ω of the previous values. Also, the isolation readings on side A and B indicate that there is no current being transferred from the heaters through the chassis.

Table 2: Final resistance and isolation check values of heaters.

Heater #:	1	2	3	4	5	6	7	8	9	10
Resistance (Ω)	157.6	160.1	157.6	154.3	157.5	160.8	158.7	158.4	154.2	157.6
Isolation side A (A)	0	0	0	0	0	0	0	0	0	0
Isolation side B (A)	0	0	0	0	0	0	0	0	0	0

Table 3 shows the equilibrium thermocouple temperature measurements at different current intervals. The average outside temperature on the black surface at 1.34A was 48.05°C and 47.5°C on the white surface.

Table 3: Test 1 temperature data.

Current (A)	0 A	0.45 A	0.89 A	1.34 A	1.55 A
TC1 (°C)	22.9	25.5	34.7	48.3	59.6
TC2 (°C)	23.0	25.6	34.6	47.8	59.4
TC3 (°C)	23.1	25.6	33.7	45.8	51.3
TC4 (°C)	23.2	25.7	34.3	46.9	57.6
TC5 (°C)	23.0	25.7	35.0	48.9	60.5
TC6 (°C)	22.7	25.5	34.8	48.4	59.5
TC7 (°C)	23.2	29.8	49.6	79.0	99.3

The temperature difference through the tip at 1.34A is ~31.32°C. 1.34A is the current that the temperature measurements of both tests are compared at because the temperatures at these currents stabilized the longest. The temperature difference between the heater and outside of tip is too large because as the current increases to provide the heaters full power (50W), the temperature of the heaters will exceed the upper temperature limit of the epoxy. This level of heat will theoretically disable the operation of the epoxy. Therefore, the team decided to create a model of the same initial tip configuration, but with the inner paint under the heaters removed. This will allow direct contact between the epoxy and the aluminum once the heaters are back in place.

The paint is mainly composed of polyurethane, which has a thermal conduction coefficient of 0.209W/m-°C. This value is one of the lower conduction coefficients of the material present in the tip. By removing one layer of paint, the outside temperature will be larger because the heat has less material to dissipate through. Heat transfer through a wall of multiple layers of different material is shown in Figure 7 below. The thermal resistance for conduction of each material is summed as the denominator in Equation 1.
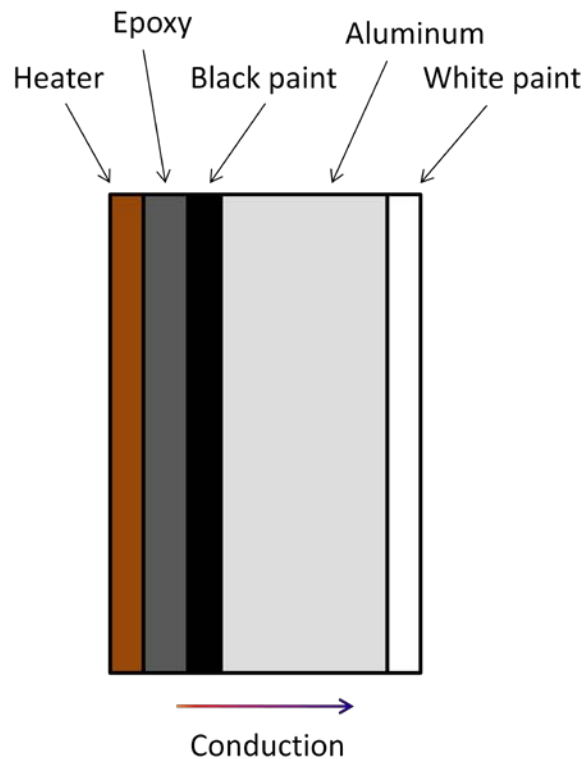

Figure 7: Drawing showing the conductive heat transfer starting with the heater on the inside of the tip through the white paint on the outside.

The thermal conductivity k can be assumed to be the same for both sides of the tip where there is black paint. That black paint thermal conductivity is calculated as 0.23W/m-K in Equation 3 and used in Equation 4 as the last unknown variable needed to calculate the white paint thermal conductivity. The assumptions used were that the thickness of the paint is the same on the inside as the outside; the heaters will have the same resistance after reinstallation; at 1.34A, there is no variance in heater temperature between this test and the last; and the aluminum is the same thickness before and after grinding off the paint. The white paint thermal conductivity resulted at 0.22W/m-K.

$$k_{black\,paint} = \frac{2L_{paint}}{\frac{\Delta T}{q''} - R_{epoxy} - R_{Al}}$$

Equation 3

$$k_{white\,paint} = \frac{L_{paint}}{\frac{\Delta T}{q''} - R_{epoxy} - R_{Al} - R_{black\,paint}}$$

Equation 4

Once all the thermal conductivities of the paint were calculated, the outer surface temperatures of the black and white paint were predicted using Equation 5 and Equation 6. The black paint surface temperature was calculated as 59.61°C and the white paint surface temperature was calculated as 59.06°C.

$$T_{out\_black\,paint} = T_{in} - q''(R_{black\,paint} + R_{Al} + R_{epoxy})$$

Equation 5

$$T_{out\_white\,paint} = T_{in} - q''(R_{white\,paint} + R_{Al} + R_{epoxy})$$

Equation 6

For the new procedure, the data collected is depicted in the tables below. The resistance values of the heaters were taken before any work was done to the tip, after the heaters were removed, and upon reinstallation (new heaters only). These are shown in Table 4 andTable 5 below. Two heaters were not salvageable and had to be replaced with new ones.

Table 4: Heater resistances before and after heater removal, and after heater install.

Heater #:	1	2	3	4	5	6	7	8	9	10
Initial Resistance (Ω)	157.7	160.3	157.7	154.7	157.5	160.9	158.9	158.5	154.4	157.7
After removal Resistance (Ω)	157.6	160.2	157.6	154.4	157.4	non-salvage	158.7	158.4	non-salvage	157.5
After install Resistance (Ω)	157.6	160.2	157.6	154.4	157.4	*new 158.7	158.7	158.4	*new 158.4	157.5

The following table presents resistance measurements and isolation checks data that were recorded after all the heaters had been installed and the epoxy cured.

Table 5: Test 2 heater resistances and isolation current post installation and epoxy cure.

Heater #:	1	2	3	4	5	6	7	8	9	10
Resistance (Ω)	157.4	160.0	157.4	154.1	157.2	158.5	158.7	158.3	158.2	157.3
Isolation (A) side A	0	0	0	0	0	0	0	0	0	0
Isolation (A) side B	0	0	0	0	0	0	0	0	0	0

The temperatures recorded from the thermocouples during the characterization test are shown below in Table 6. Thermocouples 1-7 correspond with Figure 2 and thermocouple 8 was placed on the inside surface of the tip.

Table 6: Test 2 temperature data.

Current (A)	0A	0.45 A	0.89 A	1.34 A	1.74 A
TC1 (°C)	24.7	27.0	38.4	56.3	72.1
TC2 (°C)	24.9	27.2	38.8	55.2	75.3
TC3 (°C)	24.9	27.0	37.9	53.0	71.0
TC4 (°C)	24.7	26.5	38.4	52.8	70.1
TC5 (°C)	24.6	27.0	38.7	55.3	75.7
TC6 (°C)	24.4	26.7	37.9	52.8	71.3
TC7 (°C)	24.5	28.1	42.9	59.2	82.5
TC8 (°C)	25.0	27.5	39.9	57.3	78.8

The average outside temperature on the black surface was 55.75°C and 53.46°C on the white surface. The predicted values based on the data collected in the first test (black: 59.61°C, white: 59.06°C) was closer to the actual temperatures tested in the second characterization, but was still off by 3.86°C for the black and 5.60°C for the white. The discrepancy between the predicted values and the actual values is most likely related to the assumptions made about the thickness and thermal conductivity of the paint and epoxy as well as the heater temperature remaining the same at 1.34A for both tests. Nevertheless, both the prediction from the calculated model and these new results show a decrease in outer tip temperature and more efficient heat transfer through the tip.

The overall increase in heat transfer was evident at each level of current applied because the heater temperature was a lot closer to the outer tip temperatures in test 2 than in test 1. Also, the heaters were maxed out, producing 50W at 1.74A and the temperature remained well under the epoxy operational limit of 105°C. All this is shown in Figure 8 below.
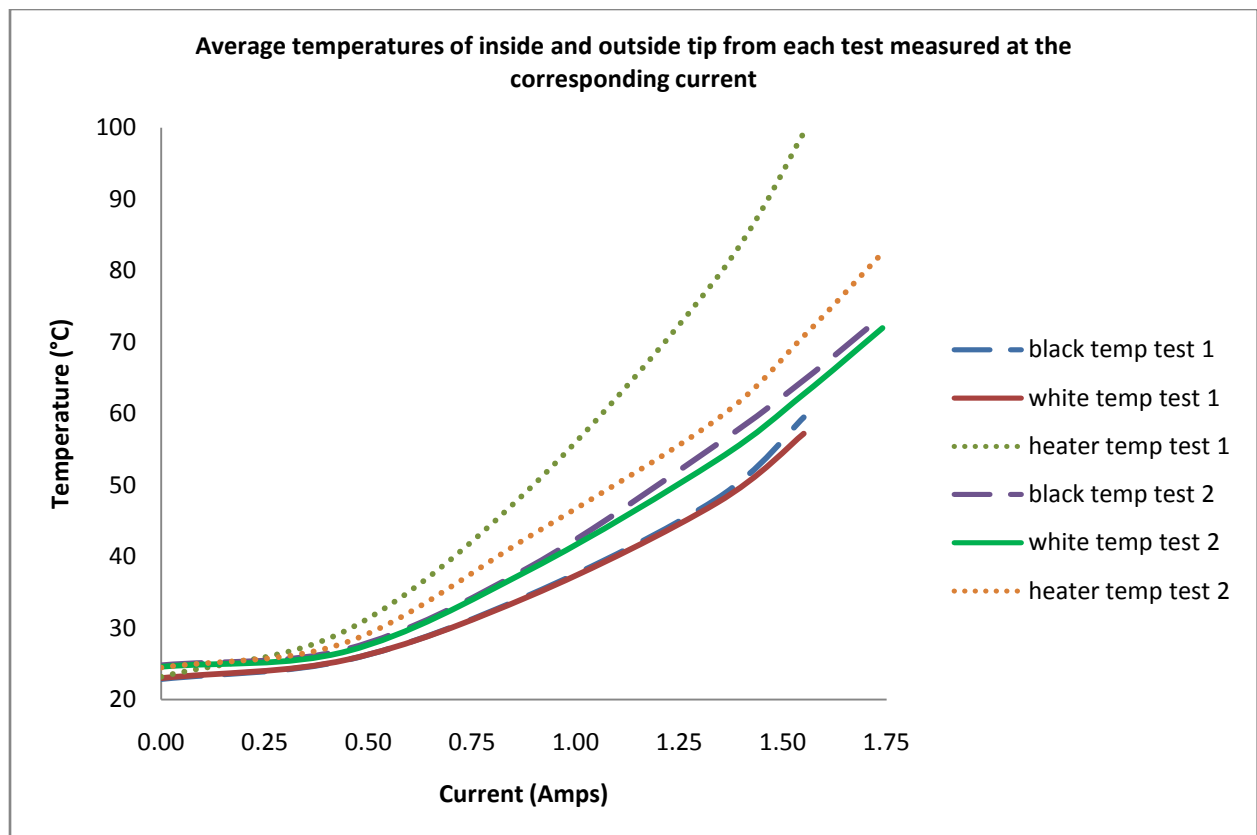
Figure 8: Average temperatures at each current level for both tests.

5.0 CONCLUSION

Heat transferred though the tip from the heaters directly on the aluminum provided a greater outer temperature with lower inner temperatures and power input. With the heaters placed over the paint as in the first characterization, the inside temperature would likely reach much greater values than 100°C. This is an excessively high temperature, especially when the outer temperature isn't even significantly greater. Therefore, the heater reinstallation and characterization proved to be a viable option because it greatly increased the heat transfer.

This test is the first of many steps to predicting the on-orbit temperature of the tip. The next step is to measure the effects due to convection and radiation, although there won't be much convection in a low-earth orbit. These orbital conditions can be simulated significantly better in a thermal vacuum chamber.

APPENDIX

Since there are now two sets of data, more accurate information can be calculated. I tried calculating the thickness of the epoxy based on the new data (temperatures and resistances) while using assumptions from the old data (thermal conductivity and thickness of the black and white paint), but came up with a very small negative number (2.22E-04m) using the black paint data. Clearly a negative thickness is not physically possible, so I assume the error is in one of the assumed values. The equation I used to calculate it was:

$$L_{epoxy} = K_{epoxy}\left(\frac{\Delta T}{q''} - \frac{L_{black\,paint}}{K_{black\,paint}} - \frac{L_{Al}}{K_{Al}}\right) \qquad \text{Equation 7}$$

Some of the conclusions I drew about which assumptions could be off are either the temperature difference is too low by at least 8°C, the thickness of the paint or heat transfer per square meter is too large by a factor of at least 4, or the thermal conductivity of the black paint is too small by a factor of 4, or a combination of the three (each to a lesser degree). These changes yield positive value for the thickness of the epoxy, so they would be worth studying.

K.al	k.epoxy_1st	k.epoxy_2nd	K.polyurethane	L.al		
130	1.22	1.44	0.209	0.001		
L.paint	L.epoxy	h.out	i.heaters	r.heaters		
5.08E-05	0.0003	10	1.34	157.42		
p.heaters	A.heaters	q".heater	delta_T_blk	delta_T_wht		
282.663352	6.45E-03	4.38E+04	30.95	31.5		
R.epoxy_1st	R.epoxy_2nd	R.blk paint	R.al	R.wht paint		
0.000245902	0.000208333	2.26E-04	7.69231E-06	2.39E-04		
K.blk paint	K.wht paint		T_o_blk_predict	T_o_wht_predict		
0.224372266	0.212585		59.62	59.07		

1st Test Data

Current (A)	0A	0.45 A	0.89 A	1.34 A	1.55 A	1.74 A
TC1 (°C)	22.882	25.5	34.7	48.3	59.6	48.3
TC2 (°C)	23	25.6	34.6	47.8	59.4	48
TC3 (°C)	23.1	25.6	33.7	45.8	51.3	45.8
TC4 (°C)	23.2	25.7	34.3	46.9	57.6	46.9
TC5 (°C)	23	25.7	35	48.9	60.5	48.5
TC6 (°C)	22.7	25.5	34.8	48.4	59.5	48.2
TC7 (°C)	23.199	29.8	49.6	79	99.3	98

Heaters #:	1	2	3	4	5
Resistance (Ω)	157.6	160.1	157.6	154.3	157.5
	6	7	8	9	10
	160.8	158.7	158.4	154.2	157.6

i.heaters	r.heaters	p.heaters	A.heaters	q".heaters	delta_T_blk	delta_T_wht
1.34	157.22	282.304232	6.45E-03	4.38E+04	3.495	5.7825
	T_o_blk_actu	T_o_wht_actual			L_epoxy_blk	K.blk paint
	55.745	53.4575			-2.22E-04	-0.37310925

2nd Test Data					
Current (A)	0A	0.45 A	0.89 A	1.34 A	1.74 A
TC1 (°C)	24.67	26.97	38.36	56.25	72.07
TC2 (°C)	24.93	27.24	38.83	55.24	75.25
TC3 (°C)	24.93	26.97	37.87	52.95	70.96
TC4 (°C)	24.7	26.53	38.38	52.77	70.11
TC5 (°C)	24.61	27.01	38.69	55.34	75071
TC6 (°C)	24.35	26.7	37.87	52.77	71.3
TC7 (°C)	24.54	28.13	42.94	59.24	82.45
TC8 (°C)	24.96	27.46	39.92	57.27	78.73
Heaters #:	1	2	3	4	5
Resistance (Ω)	157.4	160	157.4	154.1	157.2
	6	7	8	9	10
	158.5	158.7	158.3	158.2	157.3
	new			new	

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